NBS TECHNICAL NOTE 923

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Applications of Thermography for Energy Conservation in Industry

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APPLICATIONS OF THERMOGRAPHY FOR ENERGY CONSERVATION IN INDUSTRY

C.W. Hurley and K.G. Kreider

Infrared thermography has been developed as a tool to measure the temperature of various types of surfaces. Notable applications include thermal detection of diseases such as cancer and circulatory problems in human beings, aerial land mapping of hot surfaces to detect thermal pollution and geological formations, and remote scanning of buildings to detect heat losses. More recently, infrared scanning has been used to detect defects in high amperage electrical connections, transformers, and steel processing furnaces in industrial environments.

It was the intent of the NBS IR program to build on these technologies to assist energy conservation engineers to assess heat losses in industrial plants. IR teams from the NBS Center for Building Technology had previously used the equipment to survey heat losses in buildings where the IR camera was found to be particularly useful in detecting infiltration problems, missing insulation, and construction defects. Our intent in this project was to survey furnaces and heating systems in addition to electrical and mechanical systems to find areas suggesting energy conserving actions. This qualitative survey has been found to be an excellent method to detect heat losses in unit process equipment and auxiliary systems. This survey method described in this paper was carried out in fifteen industrial plants in order to develop a methodology and examine the feasibility of the approach.

In addition to the qualitative survey quantitative data was gathered by calibrating the temperature of the "hot spots" uncovered in the survey. This information was very useful in developing priorities and estimating the magnitude of the heat loss due to a given defect.

Key words: Energy conservation; energy surveys; infrared; non-destructive evaluation; thermographic surveys; thermography

Introduction

Thermography has been developed as a tool to measure the temperature of various types of surfaces. Notable applications include thermal detection of diseases such as cancer and circulatory problems in human beings, aerial land mapping of hot surfaces to detect thermal pollution and geological formations, and remote scanning of buildings to detect heat losses. More recently, infrared scanning has been used to detect defects in high amperage electrical connections, transformers, and steel processing furnaces. These techniques were reported in an ASTM "Symposium in Thermal Imaging"[1] by several groups active in the field. A review of "Thermal Infrared Scanning Capabilities" has been made by Adler and Loew.[2]

It is the intent of the NBS IR (Infrared) Program to build on these technologies to assist energy conservation engineers to assess heat losses in industrial plants. IR survey teams from the NBS Center for Building Technology (CBT) had previously used the equipment to survey heat losses in buildings. It has been found by the CBT studies that the IR camera is particularly useful in detecting infiltration problems, missing insulation, and construction defects in a similar way to that developed by Pettersson and Paljak.[3] The intent in this project was to survey heating systems in industrial plants in addition to the electrical and mechanical systems to find areas suggesting energy conserving actions. This qualitative survey has been found to be an excellent method to detect environmental heat losses in process equipment and auxiliary systems. The survey described in this report was carried out in 16 industrial plants in order to develop a methodology and examine the feasibility of the approach. These plants included tire manufacturing, cement plants, a copper refinery, forging plants, foundries, refractory and facing brick plants and heavy equipment manufacturing.

In addition to the qualitative survey, quantitative data was gathered by calibrating the temperature of the "hot spots" uncovered in the survey. These "hot spots" result from problems in the basic insulation design, flaws in the insulation and maintenance errors. However, many "hot spots" indicated malfunctions in the equipment such as leaking valves, leaking electrical components, failures in materials and components in invisible areas of the equipment, overheated bearings, etc. This information was very useful in developing priorities and estimating the magnitude of the heat loss due to a given defect. This approach applies the standard calibration methodology developed by equipment manufacturers for quantitative determinations of surface temperatures. Examples of this approach are featured in this report.

A third technique has been explored with high energy consuming equipment such as furnaces. Here, the IR scan was used to survey the entire radiating surface of a furnace. Thermal mapping was combined with area measurements to determine total radiation heat losses. This information was then used as input data for a heat balance on the furnace. One experiment has indicated that approximately 30% of the heat consumed by the furnace is being lost from the surfaces by radiation. Further work is planned in this area to develop the method and will be reported in a later publication.

Fundamentals of Thermography

Thermography can be defined as a technique of portraying an object using the thermal energy radiating from the surface of the object. The instrumentation consists of an IR camera and one or more monitors to display the area being scanned. The major difference between closed circuit television (CCTV) and thermography is that the thermographic camera scans an area for invisible infrared radiation and not for visible light. A schematic diagram of the typical thermographic system is shown in Figure 1. The area of interest is scanned through a special optical lens which will transmit the long-wave IR signals. The scanning is accomplished by rotating reflecting or refracting prisms and/or oscillating IR reflecting surfaces which project minute portions of the area being scanned on an IR detector. A review "Infrared Detectors in Remote Sensing" was presented by Levinstein and Mudar.[4] The IR detector is maintained at a low temperature -196°C (-321°F) by liquid nitrogen to increase its sensitivity and stability. The scanning mechanism makes horizontal sweeps across the surface being scanned. The lines are progressively stepped down to cover the entire surface. The scanning mechanism moves very rapidly making as many as 25 complete frames each second. Each frame consists of from 100 to 525 horizontal scan lines depending upon the design of the system.

The signals from the IR detector are amplified and transmitted to the monitor where they are further processed to produce visible light on the surface of a cathode ray tube (CRT).

The intensity of the light on the screen of the monitor is representative of the magnitude of the invisible IR signal being projected at that instant on the IR detector. The horizontal and vertical sweeping of the electron beam in the CRT are synchronized with the scanning mechanism in the IR camera. Thus, real-time, visible images of the area being scanned by the IR camera are projected on the screen of the monitor. The image on the screen is photographed to record the thermal image in the form of a thermogram.

SCHEMATIC DIAGRAM OF THERMOGRAPHIC SYSTEM

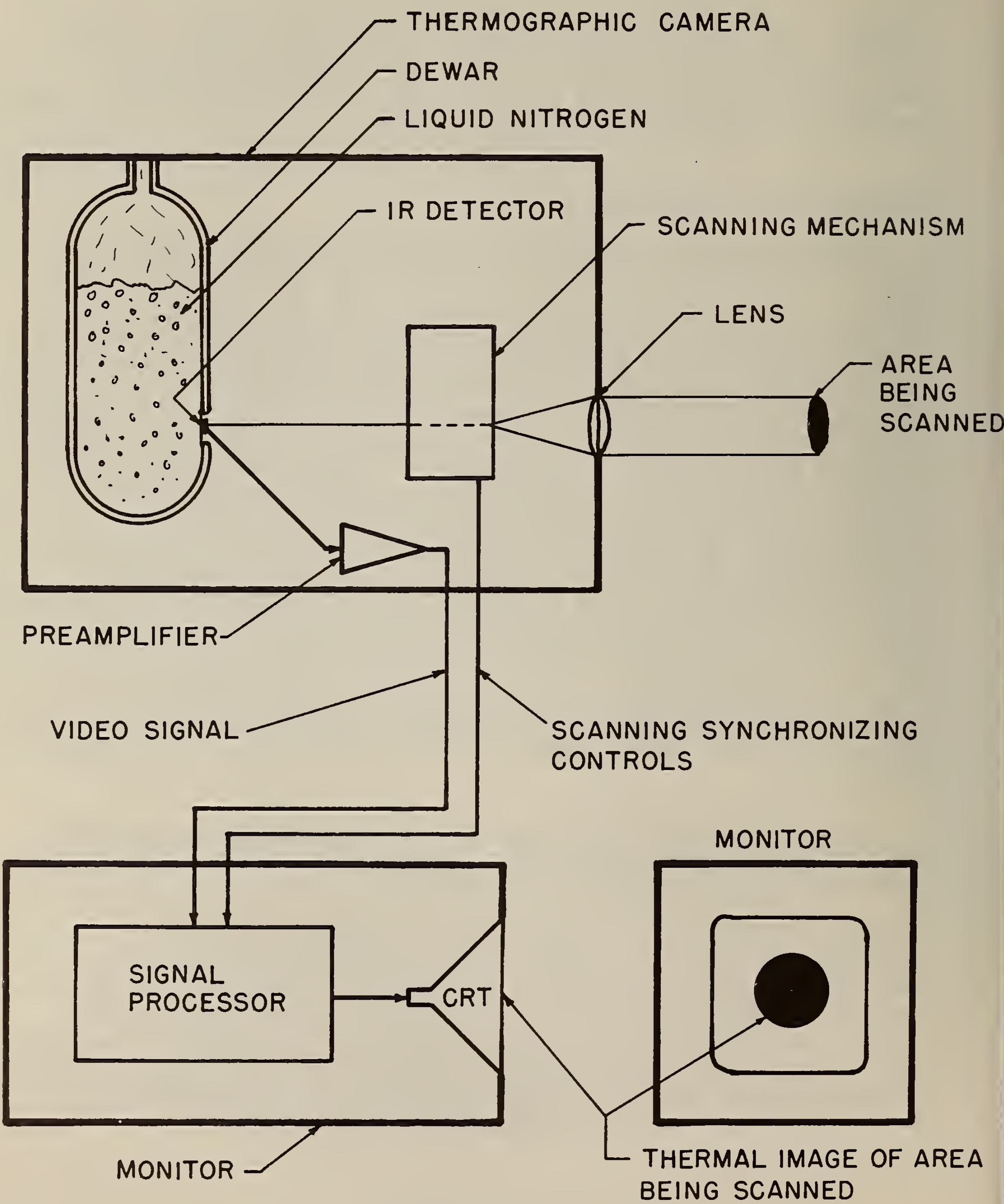


FIGURE 1

Figure 2

Monitors are also used which display the thermal image of the area being scanned by the camera in eight or ten different colors. The different colors approximately represent different temperature ranges. Profile monitors are also available which produce a contour presentation of the thermal display or a temperature profile across any selected horizontal scanning line in the thermal image. Temperature is displayed as a vertical displacement on the line. A photograph of the thermographic equipment used in the survey by the NBS IR team is shown in Figure 2.

The energy losses by thermal radiation from the surfaces of industrial processing equipment are frequently neglected. These losses exceed the losses by natural convection at temperatures above the 150°F - 200°F (65°C - 95°C) range. At temperatures above 600°F (315°C), the heat losses by thermal radiation are very high and losses by convection can usually be neglected.

Thermal radiation exhibits all of the physical characteristics of light in that it is propagated in straight lines; it can be reflected, refracted, polarized; and it can exhibit interference patterns. Since visible light and thermal radiation consist of electromagnetic waves, the major difference is the wavelength. As shown in Figure 3, solid bodies emit different levels of thermal radiation of varying wavelengths depending upon their temperatures.

As the temperature of the body is increased, energy is radiated at a much higher rate, and at shorter wavelengths. Further increases in temperature lead to the emission of red light, which is joined by the yellow, green, blue and violet components in the visible band. An ingot of iron heated to 1800°F (982°C) would have a bright orange appearance. However, only about 65 millionths of the energy radiated by the ingot would fall within the visible band.

Figure 3 illustrates the relative radiated energy for "blackbodies" at various temperatures. A blackbody absorbs all thermal radiation striking it. A blackbody is also a perfect radiator. The Stefan-Boltzmann law states that the amount of radiation emitted from a blackbody per unit time is proportional to the fourth power of the absolute temperature. A blackbody is a limiting case which is never quite reached by an actual body. An actual body, such as a solid or liquid, radiates less than a similar blackbody at the same temperature. Therefore, it is necessary to introduce a factor corresponding to the actual emission of radiant energy from the surface of a solid or liquid divided by the emission from a similar blackbody. This factor is called the emissivity and is often designated by the symbol "ε". Also the hot object being considered is surrounded by environment which also radiates according to the Stefan-Boltzmann law. To allow for these various effects, the Stefan-Boltzmann law may be expanded to the following expressions:

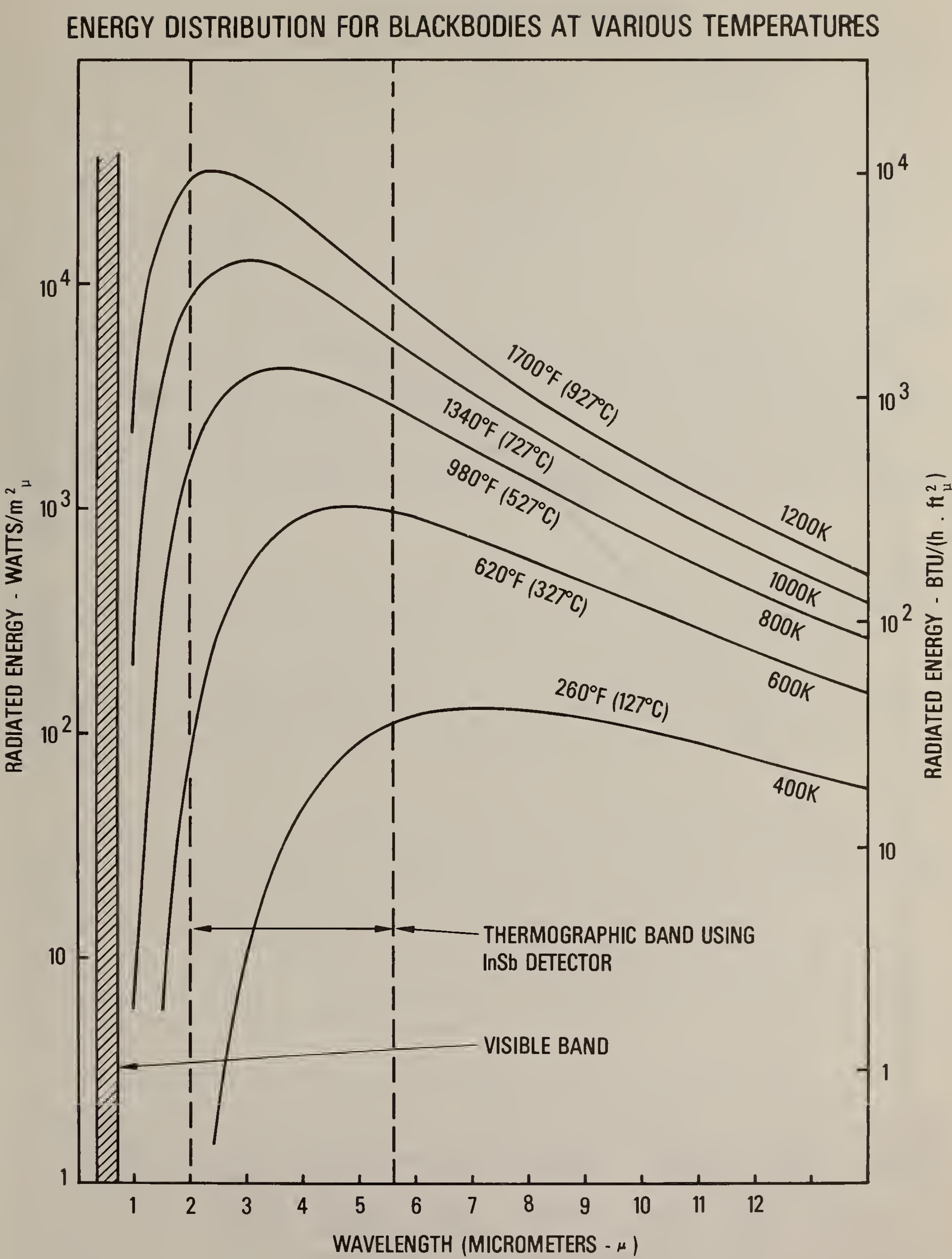


Figure 3 Energy Distribution for a Black Body at Various Temperatures

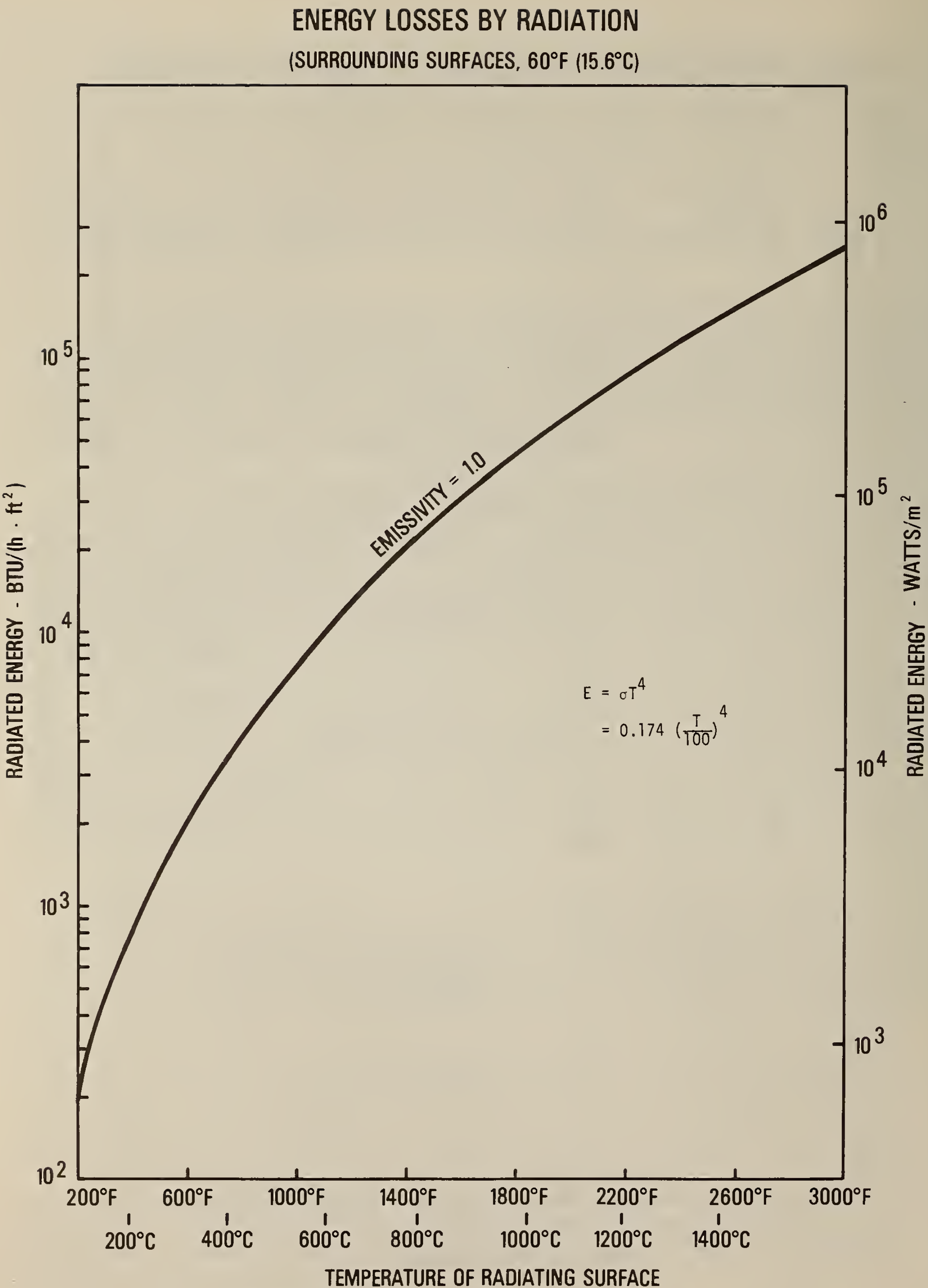


Figure 4. Energy Losses By Radiation (Surrounding Surfaces, 60°F (15.6°C)

$$E_B \ \frac{\text{Btu}}{\text{ft}^2\text{-hr}} = .171\,\varepsilon_1 \left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right]$$

or

$$E_W \ \frac{\text{Watts}}{\text{m}^2} = 5.67\varepsilon_1 \left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right]$$

The factors .171 and 5.67 are the Stefan-Boltzmann constants for the respective equations. ε_1 is the emissivity of the radiating body. T_1 is the absolute temperature of the emitting body and T_2 is the absolute temperature of surrounding bodies. The T values in the first equation are in degrees Rankine which are equal to the temperature on the Fahrenheit scale plus 459.69, and, in the second equation, the T values are in kelvins which are equal to the temperature on the Celsius scale plus 273.15.

In observing the curves in Figure 3, it will also become apparent that many materials used in industrial processes will absorb thermal radiation in one wavelength band and re-emit in another wavelength band. For example, metals being elevated in temperature by high temperature sources, such as steel under an impinging flame in a slot furnace, will absorb thermal radiation at the shorter wavelengths and, when they are allowed to cool in under typical ambient conditions, the metals will emit at longer wavelengths.

Figure 3 also illustrates the visible wavelength band and the wavelength band of thermographic equipment using the indium antimonide (In Sb) infrared detector. Although other high speed IR detectors are commercially available which allow the area to be scanned within a different wavelength interval, the limits of their sensitive band do not lend themselves to the typical elevated temperatures in the industrial field. For example, the human body radiates at approximately 310°K. At this temperature only about 2.4% of the total energy radiating from the body would fall within the InSb band.

Thermography is often confused with infrared photography. The maximum sensitive wavelength for commercially available infrared photographic film falls between .8 and .9 micrometers. By observing the energy distribution curves shown in Figure 3, it will be noted that surfaces radiating thermal energy in these shorter wavelengths are very hot and other heat sensing equipment such as optical pyrometer can be used. Infrared photography is generally used to display reflections from the sun, a tungsten filament, or other very hot object. Reflections of this type and reflections from objects at still lower temperature often hinder in obtaining thermograms of industrial surfaces of interest.

Figure 4 illustrates the energy lost per unit area of a radiating surface which has an emissivity of unity when the temperature of the surrounding surfaces is 60°F (15.6°C). The emissivity factors of typical materials found in an industrial plant at elevated temperatures are given in Table 1. The energy lost per unit area by thermal radiation can be estimated from the graph of Figure 4 by multiplying the energy values shown for the various surface temperatures by the emissivity factor of the surface. It will be noted that the emissivity factors for typical radiating surfaces do not drastically reduce the losses shown for surfaces with an emissivity of unity. If the temperatures of surrounding surfaces vary greatly from the 60°F (15.6°C) value used in plotting the chart shown on Figure 4, and more exact values are desired, it may be necessary to replot the chart using the radiation exchange equations and inserting the actual values for the existing conditions.

Performing Thermographic Surveys in Industrial Plants

In performing the IR thermography surveys certain general procedures were followed. Equipment operation itself is well prescribed by the manufacturers but many other factors were important to obtaining useful results.

First, the opportunities for uncovering thermal loss problems in the plant were discussed with the management, engineering and operation personnel. Examples of past studies were reviewed to familiarize all concerned with the intent of the survey. It was found useful to discuss plant operations and equipment with special emphasis on energy fluxes within the plant.

A "walk-through" with plant personnel was found useful in selecting targets for scanning. Items such as furnaces, kilns, ovens, boilers, hot conveyors, flues, bearings, electrical junctions and transformers, and other hot spots were noted and special operation or maintenance problems were discussed. The IR cameras were then set up and the equipment calibrated with reference temperature surface measurements. Conventional photography in the visible spectrum was used in conjunction with the IR thermography for identification of the location of the thermal information. Emphasis was placed on setting the hot spot of the field at the top of the temperature range with the full range selected to include dark areas which could be neglected due to low thermal output. Optimal range and scale selection requires considerable skill and multiple ranges were often chosen.

The identification of the hot spots and their causes was generally accomplished during the scanning operation. The use of the color monitors with on site operating personnel was extremely useful in the interpretation and analysis of the results. Also, this energy-relevant information was particularly useful to the plant operating personnel.

Although thermography has many advantages, some of the limitations were recognized during the surveys. A thermogram of the surface of any object will indicate only the relative temperatures of each area. The temperature of a reference area within the surface in the thermogram is necessary to obtain quantitative readings. Further, the emissivities of the surface used as a reference and the surface of interest must be known. In general, a surface is available within the area being scanned that is suitable for a reference source. However, the temperatures of the reference surface and the surface of interest must be within the "gray scale" of the thermogram; i.e., if either surface is in the black or the saturated white areas of the scale, quantitative temperature readings cannot be obtained. This limitation is only objectionable when the range of temperatures of the object in the thermogram is very large.

Reflections from other equipment, lights, the sun, etc., can limit the use of thermography on equipment with IR reflective surfaces. Examples include food processing plants and breweries. A typical example of such reflections from adjacent equipment was experienced during the NBS survey while observing the limited radiation losses from a well insulated steel tempering oven. An electrical junction box about two meters from the oven appeared to be very hot and electrical problems were immediately suspected. However, when the junction box was examined, it was found at ambient temperature. It was also found to be a new, clean, zinc covered junction box. Table 1, indicates an emissivity of .23 is typical for such surfaces which means that 77% of the thermal radiation striking the box is reflected. The artifact was easily blocked out of the thermogram by shielding the box from the radiation from another oven. The surfaces of interest in the vast majority of industrial plants do not exhibit this reflection characteristic.

Glass exhibits several unique characteristics that must be considered in thermography. From Table 1, it will be noted that glass has a relatively high emissivity, 0.85 to 0.95. Also, the transmission of infrared radiation through glass is high for wavelengths less than 3 micrometers, and drops off rapidly with increasing wavelengths. Glass is completely opaque for wavelengths greater than 4.5 micrometers. In observing the sensitive band pass for the InSb detector shown in Figure 2, it becomes obvious that transmission must be considered if a radiating surface behind the glass is very hot and if the surface is being observed by the thermographic camera through the glass. Solar reflections from glass and other surfaces must also be considered in thermography. These reflections hinder measurements at wavelengths less than 3.5 micrometers. Filters are available to eliminate problems from solar reflections. To eliminate the thermal radiation transmitted through glass filters are available which allow only the radiation from the surface of the glass to reach the IR sensing element. The unique infrared characteristics of glass must be considered when it is one of the materials being scanned.

Plastics such as polyethylene also exhibit unique characteristics. Although these materials are almost completely transparent in the band pass of the InSb detector, there is a narrow absorption peak which occurs at a wavelength of 3.43 micrometers. If the plastic is the surface of interest, again, a narrow band pass filter will be required.

Results of NBS Industrial Thermographic Surveys

Several hundred thermograms were accumulated during the industrial surveys made by the NBS teams. A limited series of thermograms are presented to demonstrate some of the typical applications of thermography in the industrial field.

Tunnel kilns and other continuous processing equipment present excellent examples of industrial processes which require a complete shut down of the operation before an inspection can be made for a suspected fault causing defects in the product being produced. Figure 5 is a photograph of the side of a section at the output end of a relatively small tunnel kiln used to fire building bricks. Although the outer structure of the kiln did not indicate any irregularities, the operator had found it necessary to modify the cooling section of the kiln to prevent the product from fracturing due to cooling too rapidly.

Figure 6 is a thermogram of the section shown in Figure 5. The thermogram shows one of several sections of the sides at the output end of the kiln indicating areas where the refractory material lining the inside of the kiln had fallen. Thermographic scanning of this kiln gave the plant manager immediate information on problems concerning the continually increasing fuel consumption of the kiln and the extremely large percentage of the brick that had to be discarded because of thermal fracture. The plant engineer closed the kiln, made the necessary liner repairs, and the kiln was found to work properly after the repair.

Figure 7 is a photograph of a small section of a large tunnel kiln that had been repaired. However, the refractory brick that was used to repair the opening was of a different type from that originally used and was inferior in insulating properties. Figure 8 is a thermograph of the repaired area and indicates the heat losses through the repair brick.

Figure 5. Outer wall of the exit of a small tunnel kiln used to fire building brick. Inner walls and ceiling constructed of refractory brick.

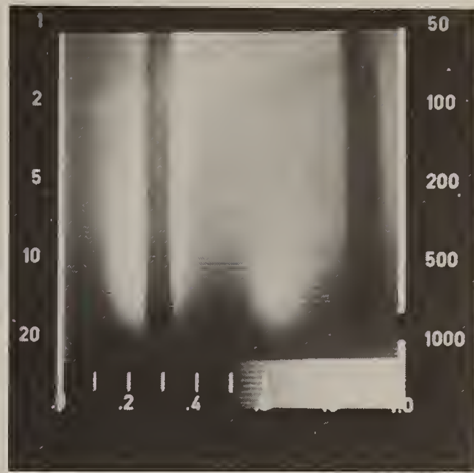


Figure 6. Thermogram, light areas indicated elevated surface temperature of the outer structure caused by failure of the inner refractory brick.

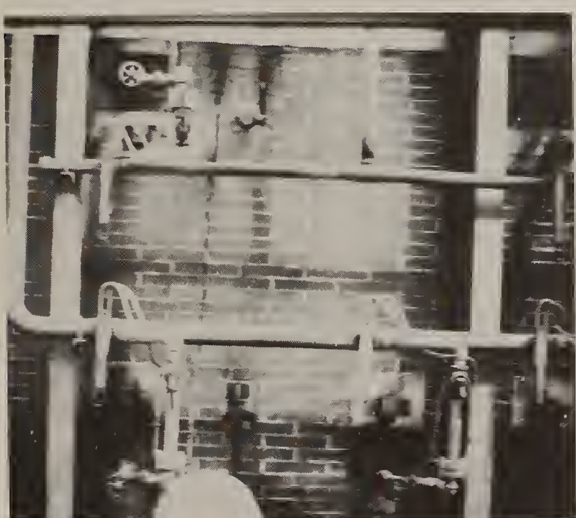


Figure 7. Portion of the burner section of a large tunnel kiln. The refractory brick around the burners had been removed for burner modification.

Figure 8. Thermogram, note the excessive radiation from the outer structure of brick caused by conduction from the improper refractory brick used to replace the brick around the burner.

Figure 9 is a photograph of a section of a much smaller tunnel kiln used to fire individual sections of high temperatures refractories. In this section of this kiln, the inside temperatures exceed 3000°F (1650°C) and the walls, ceiling and floor are heavily insulated. This photograph shows the plumbing for the gas and preheated air for the burners in this section. Figure 10 is a thermogram of this same section of the kiln showing excessive thermal radiation in the areas of the burners and areas where the insulation is inadequate or failing. The temperature of the larger area showing excessive radiation in the upper left hand section is approximately 450°F (230°C). Another section of this same kiln is shown in the photograph in Figure 11. The offset in the outside wall represents an increase in the thickness of the insulation to reduce the losses from the hotter section of the kiln. The section at the right hand side of the photograph is the input section of the kiln. Figure 12 is a thermogram of this section of the kiln indicating a refractory failure in the upper portion of this offset. It should be noted that internal failures of this type can be recorded only by scanning the entire surface of the kiln with the thermographic camera.

A photograph of a typical process steam boiler found in industry is shown in Figure 13. This is one of many process steam boilers originally designed for burning coal but modified to burn oil or natural gas. A thermogram of this view of the boiler is shown in Figure 14. Although the side of the boiler is well insulated, the bonnet is radiating at approximately 450°F (230°C) and the uninsulated sections of the valves were found to be 320°F (160°C). When compared with many types of energy consuming equipment in the industrial field, process steam boilers, in general, operate at relatively high efficiencies. However, when large areas are observed radiating at higher temperatures such as the boiler bonnet in this example, and the temperature of the flue gas was measured at 585°F (310°C), there is always room for improvement.

Figure 15 is a photograph of a typical indirect heating oven used in many industrial processing applications. The section shown in this photograph is the area of the oven where the heat exchanger is located.

A thermogram of this same area shown in Figure 16, indicates good insulation between the heat exchanger and the panels of the outer shell. However, the "thermal bridges" formed by the sections of the outer panels for retention can be observed. The areas around the maintenance door were found to be 320°F (160°C) with a thermocouple. The gas burner mounted on the fire box on top of the oven can be observed at the top of the ladder in the photograph. The radiation from the outer portion of the burner is shown by the saturated area in the upper corner of the thermogram.

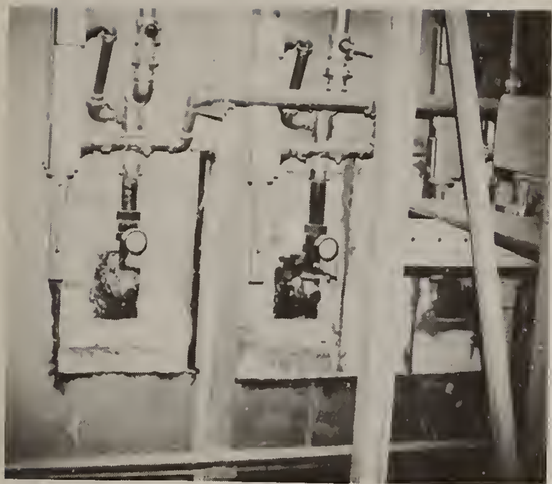


Figure 9. Section of small high temperature tunnel kiln. This photograph shows three of the burners in this section of the kiln.

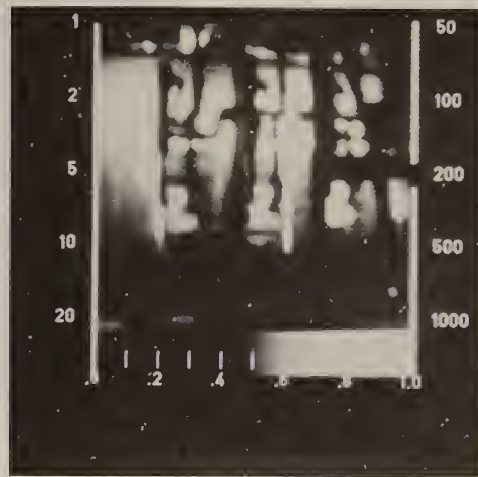


Figure 10. Thermogram of the section of the kiln.

Figure 11. Input section of high temperature kiln. Note the electrical box and the thermocouple fixtures at the offset of the kiln.

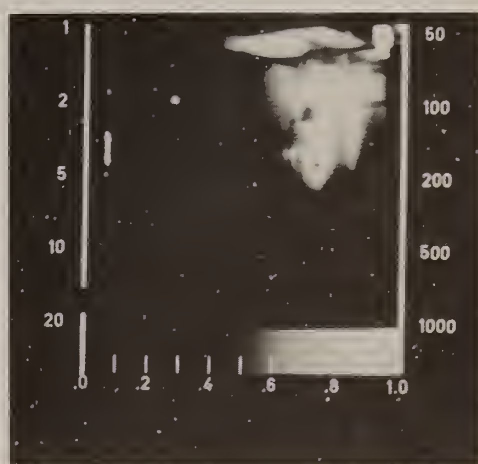


Figure 12. Thermogram. The internal refractory brick had fallen in portions of this section of the kiln.

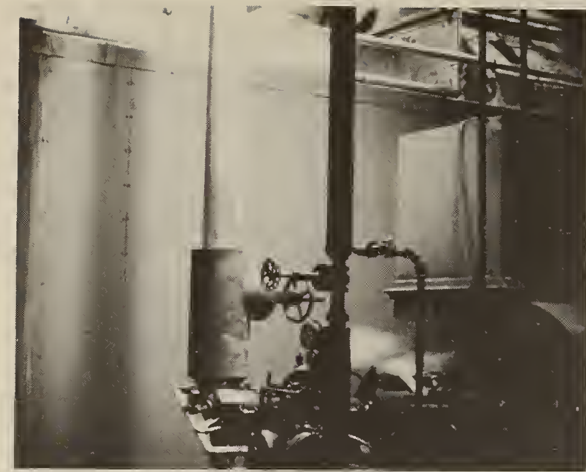


Figure 13. Process steam boiler. Steam drum is shown at the top of the photograph. Exhaust bonnet is shown in the upper left corner of the photograph.

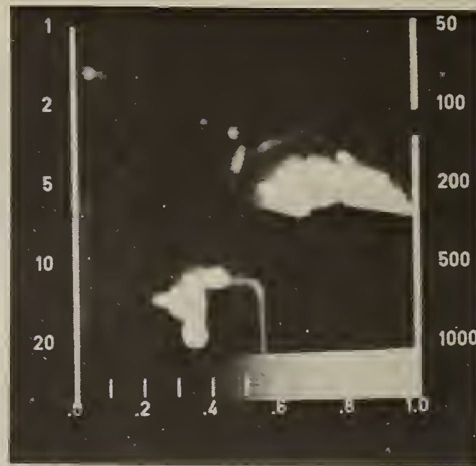


Figure 14. The bonnet and the uninsulated portions of the valve indicate elevated temperatures.

Figure 15. Typical oven used to elevate the temperature of products by indirect heating. Note the single burner in the heat exchanger on top of the oven.

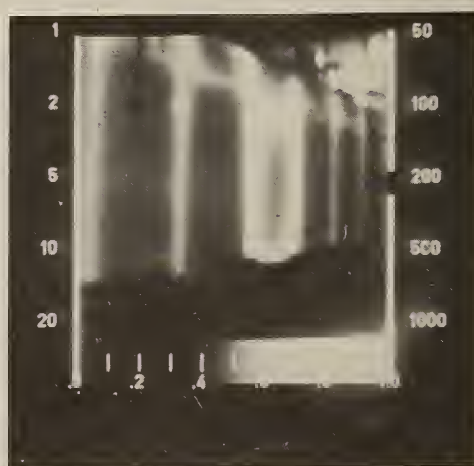
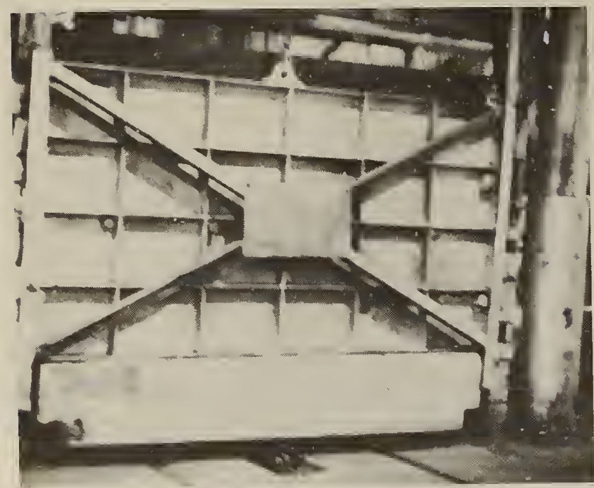


Figure 16. Elevated temperatures are noted in the area of the burner and around the maintenance door.

Figure 17 is the door of a car bottom furnace in operation. This furnace is approximately 8 feet, (2.5 m) high, 13 feet (4 m) wide and 19 feet (5.8 m) deep, and is considered a small to medium size furnace in the steel industry. The door on the furnace shown in Figure 17 is not attached to the car as in the typical design of this type furnace. The door is elevated to remove the flat car. A thermogram of this door is shown in Figure 18. At the time this thermogram was recorded, the furnace had already heated steel billets on the car to 2300°F (1250°C) and was operating to retain the billets at that temperature. The hot gases indicated by the saturated area on the thermogram at the top and bottom of the door indicate inadequate sealing in these areas. The surface of the door was measured at 470°F (243°C). The temperature of the cross bracing was 270°F (100°C).

Figures 19 and 20 are thermograms of the doors of large car bottom furnaces where the door was integral with the car. These furnaces were retaining the temperature of large steel billets at 2300°F (1260°C). Although these furnaces were identical in size and design, the furnace in Figure 20 had just been rebuilt and the furnace in Figure 19 was scheduled to be rebuilt in the near future. The failure of some of the refractory materials is evident in Figure 19. However, both thermograms indicate excessive heat losses around the 2 to 5 inch (5 to 13 cm) gap around the door to compensate for the irregularities in the track on which the car is rolled in and out of the furnace. Furnaces of this type are generally used for periodic cycling and the excessive thermal mass reduces the thermal efficiency. However, the efficiency of such furnaces can be improved by using flexible high temperature insulative material to seal the doors and reduce infiltration in other areas; loading the furnaces to full capacity for each cycle; and, reducing the time between unloading and reloading. The lower thermal conductivity and the lower density of ceramic fiber furnace lining materials now available should be considered in rebuilding furnaces of this type.

The low efficiencies of slot furnaces used in forging shops are often referred to in energy conservation papers. However, the losses that are caused by improper burner adjustment are often neglected. Since several of the absorption bands of carbon dioxide and water vapor are within the sensitive waveband of the InSb detector, the IR camera will indicate radiation from these hot compounds found in exhaust fumes unless special filters are used. An example of how thermography can be used to detect improper burner adjustment is demonstrated on the small two burner commercial slot furnace shown in Figure 21. This furnace was being used in a small forging shop to heat a series of small billets placed along the bottom of the furnace. Figure 22 is a thermogram of the area just above the front shield of the furnace where the exhaust gases escape. The thermogram indicates excessive hot exhaust gases from the left burner. When the operation of the furnace was observed from the side of the furnace, the flame from the left burner was projecting upwards behind the shield and visible outside of the slot.



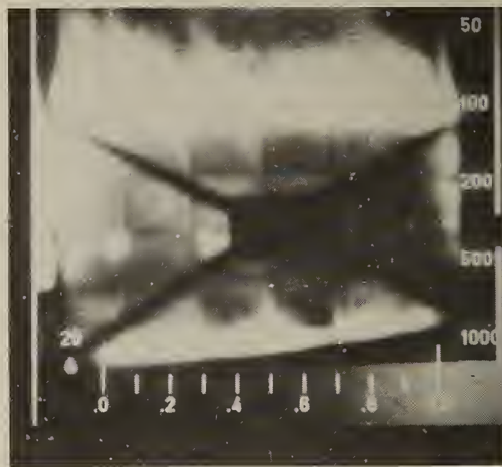


Figure 17, 18. Door of a car bottom furnace in operation. The steel billets inside had already been heated to a temperature of 2300°F (1260°C) in this furnace and, at the time of this photograph, the furnace was operating to retain the billets at this temperature.

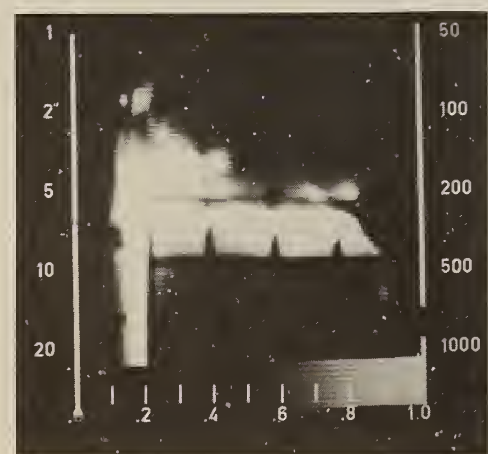


Figure 19. Door of a large car bottom furnace retaining the temperature of steel billets at 2300°F (1260°C). The upper section of the door indicates failure in the refractory material.

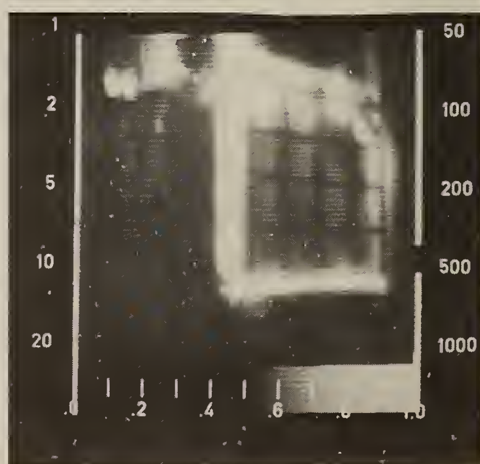


Figure 20. Door of a large car bottom furnace identical to that shown in Figure 18 except this furnace has just been rebuilt. The radiation around the door is from the relatively large clearances allowed for opening and closing the furnace.

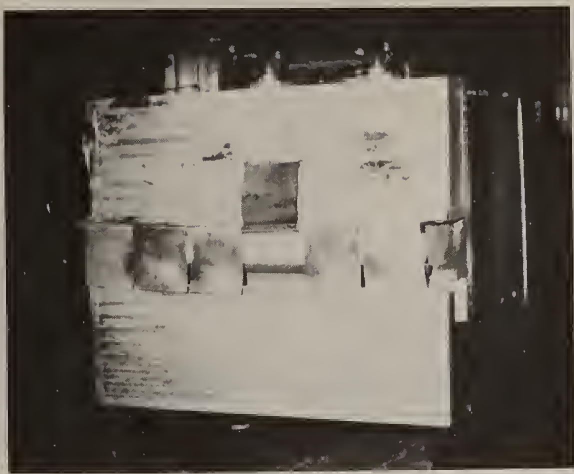


Figure 21. Small, two burner slot furnace used in a small forge shop. One of the shielding flaps is open. Note the two burners at the top of the furnace.

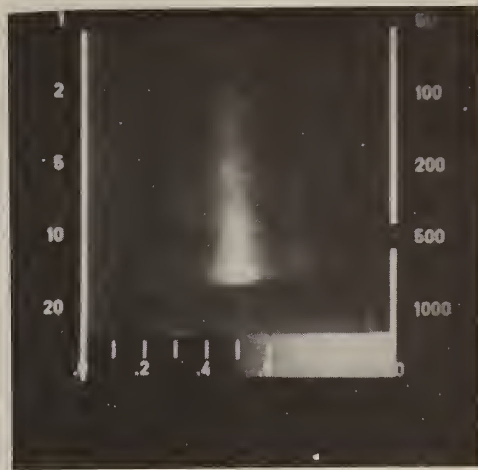


Figure 22. Top of the furnace shown in Figure 21. This thermogram indicates excessive overflow from the left burner.

Figure 23 is a photograph of an identical type slot furnace in the same forging shop. A thermogram of this furnace is shown in Figure 24.

The radiation from the flame can be observed in the area of the slot and from the exhaust gases from both burners. The results of this simple survey in this forging shop allowed the operator to adjust the burners on both furnaces to bring the impinging flame back into the slot where the steel billets were being heated. This survey also convinced the operator and the management that the very old philosophy of the eye being the best tool for burner adjustment was no longer sound and a simple thermocouple instrument was purchased to check the burners periodically. This action resulted in a 60% reduction in gas consumption in this shop.

The negative pressures generated in industrial furnaces are often the cause of large heat losses from infiltration. The flue shown in Figure 25 is attached to a reverberation furnace used to retain an aluminum alloy in a molten state. A thermogram of this flue, shown in Figure 26, allowed the temperature of the flue gases to be measured at 2300°F (1260°C). The temperature of the molten alloy was less than 1000°F (540°C). The thermogram convinced the plant management to investigate the equipment. Placing a simple damper in the flue with an automatic control reduced the fuel consumption by 55%.

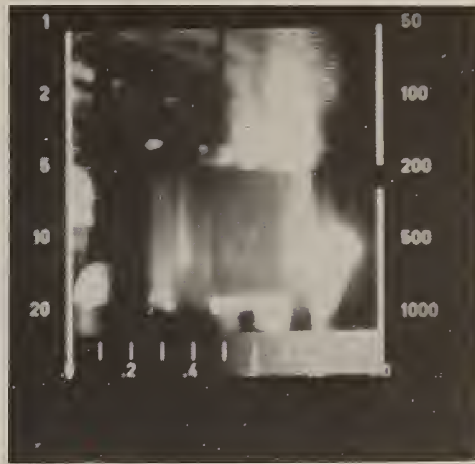


Figure 23. Slot furnace of the same design as that shown in Figure 21.

Figure 24. Excessive hot exhaust gases are indicated from both burners.

Figure 25. Flue on conventional reverberatory furnace.

Figure 26. The temperature of the flue gases were measured at 1300°F (700°C) higher than the temperature of the material being retained at a molten state in the furnace.

Summary

Thermography is a useful tool for scanning industrial equipment and processes to detect excess heat losses and malfunctions which result in temperature changes. The examples given in this paper were limited to several industrial areas where thermography is directly applicable. However, the authors feel that many industrial plants would benefit from the results of a thermographic survey. Applicable examples include: electrical systems and components; boilers; steam systems; prime movers; grinders; hot conveyors; flues; bearings; heat exchanges of all types; heat regenerators; any product being processed at an elevated or reduced temperature; processing equipment; plant walls; plant heating systems; etc.

The NBS IR industrial plant survey project has built on the technology of the IR surveys of buildings developed by Pettersson and Paljak in Sweden and the NBS experience. The industrial plant survey was related also to the plant energy survey techniques discussed in NBS handbook 115 (EPIC) with generous help from the East Ohio Gas Energy Conservation Group, 14 plants were surveyed in Ohio including tire, ceramic, forging, and metallurgical plants. Excellent cooperation by these plants and others where more quantitative surveys were conducted indicated that plant management was eager to make improvements indicated by the IR information.

It was found that frequently the identification of a high heat loss was all that was needed to make the engineering decision to correct a fault in the equipment or operating procedure which would save energy. With many of these improvements such as better balancing of the combustors as indicated with the slot furnace (Figure 20) no quantitative information was needed in order to select the corrective course of action. Other problems such as the addition of the damper in the flue of the reverberatory furnace involve minor investments but back-of-the-envelope calculations are all that is necessary to convince management of the need for the improvement after the IR picture has illustrated the problem. Some modifications suggested by the IR survey such as the repair of the failed inner refractory brick shell of the tunnel kiln are performed in conjunction with maintenance actions prescribed for reasons other than energy conservation. Here the energy savings is a happy by-product of the use of the IR survey in detecting causes for major processing problems. The IR survey was found to give excellent background information on heat losses on equipment where immediate action may not be warranted, but this information particularly when reduced to quantitative measures of heat losses is important in making future decisions on maintenance, redesign, repair, retrofitting, and replacement.

Recommendations

The initial cost of thermographic equipment has retarded the use of thermography in the industrial field for over 20 years. However, the increasing costs and curtailments of fuels have encouraged the use of thermographic techniques in industry. Rather than buying the necessary equipment at a cost of approximately $50,000, and developing an in-house team to perform thermographic surveys, many plants are finding it preferable to obtain these services from an outside contractor. Numerous organizations have been established within the past two years which specialize in performing thermographic surveys in industrial plants. The results of such surveys are usually very helpful in fuel conservation programs. Thermographic equipment is also leased by some of the leading manufacturers. This option is often desirable when qualified operating personnel are already available in the plant. Because of the significant information gain using these surveys the authors highly recommend the use of IR surveys as a tool in industrial energy conservation programs.

Table 1

Normal Total Emissivity of Various Surfaces[1]

Surface	°F[2]	Emissivity
Metals and their Oxides		
Aluminum		
Polished..........................	212	0.095
Commercial sheet.................	212	0.09
Heavily oxidized.................	200-940	0.20-0.31
Aluminum oxide...................	530-930	0.63-0.42
Aluminum oxide...................	930-1520	0.42-0.26
Aluminum alloy 7075 cleaned with toluene, then methanol, repeatedly heated and cooled...............	450-900	0.22-0.16
Aluminum alloy 2024 cleaned with toluene, then methanol, repeatedly heated and cooled...............	450-910	0.17-0.15
Brass		
Polished..........................	100-600	0.10
Rolled plate, natural surface....	72	0.06
Dull plate.......................	120-660	0.22
Oxidized by heating at 1110°F....	390-1110	0.61-0.59
Chromium, polished................	100-2000	0.08-0.36
Copper		
Polished..........................	242	0.023
Commercial, scraped shiny, but not mirrorlike.....................	72	0.072
Plate, heated long time, covered with thick oxide layer..........	77	0.78
Plate heated at 1110°F...........	390-1110	0.57
Inconel		
Type X, cleaned with toluene, then methanol, repeatedly heated and cooled..........................	450-1620	0.55-0.78
Type B, cleaned with toluene, then methanol, repeatedly heated and cooled..........................	450-1620	0.35-0.55
Iron and Steel Metallic Surfaces		
Steel, polished..................	212	0.066
Iron, polished...................	800-1880	0.14-0.38
Cast iron, polished..............	392	0.21
Smooth Sheet iron................	1650-1900	0.55-0.60

Table 1 (Con't.)

Surface	°F[2]	Emissivity
Type 310, brown splotched, oxidized from furnace service................	420-980	0.90-0.97
Tin, commercial tin-plated sheet iron................................	212	0.07-0.08
<u>Zinc</u>		
Commercial 99.1% pure, polished......	440-620	0.045-0.053
Galvanized sheet iron, fairly bright.	82	0.23
Galvanized sheet iron, grey oxidized............................	75	0.28
<u>Refractories, Building Materials, Paints and Miscellaneous</u>		
<u>Alumina</u>		
Mean grain size 10 microns...........	1850-2850	0.30-0.18
Mean grain size 50 microns...........	1850-2850	0.39-0.28
Mean grain size 100 microns..........	1850-2850	0.50-0.40
Asbestos board........................	74	0.96
Asbestos paper........................	100-700	0.93-0.94
<u>Brick</u>		
Red, rough, but no gross irregularities......................	70	0.93
Building.............................	1832	0.45
Fireclay.............................	1832	0.75
Magnesite refractory brick...........	1832	0.38
<u>Carbon</u>		
Filament.............................	1900-2560	0.526
Rough plate..........................	212-608	0.77
Rough plate..........................	608-932	0.77-0.72
Lampblack, rough deposit.............	212-932	0.84-0.78
Graphite, pressed, filed surface.....	480-950	0.98
Carborundum (87% SiC, density 2.3)...	1850-2550	0.92-0.82
Concrete tiles.......................	1832	0.63
Enamel, white fused, on iron.........	66	0.90
Glass, pyrex, lead and soda..........	500-1000	0.95-0.85
Glass,polished plate.................	70	0.94
Gypsum, 0.02 in. thick, on smooth or blackened plate..................	70	0.903
Marble,light grey polished...........	72	0.93
Oak, planed..........................	70	0.90

Table 1 (Cont.)

Surface	°F[2]	Emissivity
Mild steel, cleaned with toluene, then ethanol, repeatedly heated and cooled......................	450-1950	0.20-0.32
<u>Iron and Steel Oxidized Surfaces</u>		
Iron plate, completely rusted....	67	0.69
Iron, dark grey surface..........	212	0.31
Rolled sheet steel...............	70	0.66
Cast iron, oxidized at 1100°F....	390-1110	0.64-0.78
Steel, oxidized at 1100°F........	390-1110	0.79
Iron oxide.......................	930-2190	0.85-0.89
Sheet steel, strong, rough oxide layer.....................	75	0.80
Sheet steel, dense, shiny oxide layer..........................	75	0.82
Cast iron, rough, strongly oxidized.......................	100-480	0.95
Wrought iron, dull, oxidized.....	70-680	0.94
Steel plate, rough...............	100-700	0.94-0.97
Lead, oxidized at 300°F..........	390	0.63
Magnesium oxide..................	530-1520	0.55-0.20
Magnesium oxide..................	1650-3100	0.20
Monel 400 oxidized at 1110°F.....	390-1110	0.41-0.46
Monel K-500, cleaned with toluene, then ethanol, repeatedly heated and cooled..............	450-1610	0.46-0.65
Nickel, polished.................	212	0.072
Nickel plate, oxidized by heating at 1110°F......................	390-1110	0.37-0.48
<u>Stainless Steels</u>		
Polished.........................	212	0.074
Type 301 cleaned with toluene, then ethanol, repeatedly heated and cooled.....................	450-1740	0.57-0.55
Type 316, cleaned with toluene, then ethanol, repeatedly heated and cooled..............	450-1600	0.57-0.66
Type 347, cleaned with toluene, then ethanol, repeatedly heated and cooled.....................	450-1650	0.52-0.65

Surface	°F[2]	Emissivity
Paints, Lacquers, Varnished		
Snow-white enamel varnish on rough iron plate	73	0.906
Black shiny lacquer, sprayed on iron	76	0.875
Black matte shellac	170-295	0.91
Black or white lacquer	100-200	0.80-0.95
Flat black lacquer	100-200	0.96-0.98
Oil paints, 16 different, all colors	212	0.92-0.96
Aluminum paints and lacquers, 10% Al, 22% lacquer body on rough or smooth surfaces	212	0.52
Aluminum paint with silicone vehicle, 2 coats on Inconel	500	0.29
Other aluminum paints, varying age and aluminum content	212	0.27-0.67
Aluminum lacquer, varnish binder on rough plate	70	0.39
Aluminum paint, after heating to 620°F	300-600	0.35
Radiator paint, white, cream, bleach	212	0.79,0.77,0.84
Radiator paint, bronze	212	0.51
Lacquer coatings, clear, 0.001-0.015 in. thick on aluminum alloys	100-300	0.87-0.97
Clear silicone vehicle coatings 0.001-0.015 in. thick on mild steel	500	0.66
Plaster, rough lime	50-190	0.91
Porcelain, glazed	72	0.92
Quartz, rough, fused	70	0.93
Roofing paper	69	0.91
Rubber, hard, glossy plate	74	0.94
Rubber, soft, grey, rough, (reclaimed)	76	0.86
Silica, mean grain size 10 microns	1850-2850	0.42-0.33
Silica, grain size 70-600 microns	1850-2850	0.62-0.46

[1]Selected from a compilation by H.C. Hottel, published in Table A.23 of Heat Transmission, 3rd Edition, 1954 by W.H. MacAdams, McGraw-Hill Book Co., Inc.

[2]When temperatures and emissivities appear in pairs separated by dashes, they correspond, and linear interpolation is possible.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Infrared thermography has been developed as a tool to measure the temperature of various types of surfaces. Notable applications include thermal detection of diseases such as cancer and circulatory problems in human beings, aerial land mapping of hot surfaces to detect thermal pollution and geological formations, and remote scanning of buildings to detect heat losses. More recently, infrared scanning has been used to detect defects in high amperage electrical connections, transformers, and steel processing furnaces in industrial environments.

It was the intent of the NBS IR program to build on these technologies to assist energy conservation engineers to assess heat losses in industrial plants.IR teams from the NBS Center for Building Technology had previously used the equipment to survey heat losses in buildings where the IR camera was found to be particularly useful in detecting infiltration problems, missing insulation, and construction defects. Our intent in this project was to survey furnaces and heating systems in addition to electrical and mechanical systems to find areas suggesting energy conserving actions. This qualitative survey has been found to be an excellent method to detect heat losses in unit process equipment and auxiliary systems. This survey method described in this paper was carried out in fifteen industrial plants in order to develop a methodology and examine the feasibility of the approach.

In addition to the qualitative survey quantitative data was gathered by calibrating the temperature of the "hot spots" uncovered in the survey. This information was very useful in developing priorities and estimating the magnitude of the heat loss due to a given defect

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Key words: Energy conservation; energy surveys; infrared; non-destructive evaluation; thermographic surveys; thermography

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